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LIFE CYCLE SUSTAINABILITY ASSESSMENT: FROM LCA TO LCSA

An approach to LCSA: the case of concrete recycling

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Abstract
Purpose The framework of life cycle sustainability analysis (LCSA) has been developed within the CALCAS project but the procedure on how an LCSA should be carried out is still far from standardized. The purpose of this article is to propose an approach to put the LCSA framework into practice. This approach is illustrated with an on-going case study on concrete recycling.
Methods In the context of an EC-FP7 project on technology innovation for concrete recycling, five operational steps to implement the LCSA framework are proposed: (1) broad system definition, (2) making scenarios, (3) defining sub-questions for individual tools, (4) application of the tools and (5) interpreting the results in an LCSA framework. Focus has been put on the goal and scope definition (steps 1–3) to illustrate how to define a doable and meaningful LCSA. Steps 4–5 are not complete in the case study and are elaborated theoretically in this paper.
Results and discussion The experience from the case study shows that the operational steps are especially useful at the stage of defining the goal and scope. Breaking down the sustainability questions into different scales and different aspects gives the possibility to define the sub-questions suitable to be assessed by the individual analytical tools (e.g., LCA, LCC, SLCA, MFA, etc.). The C2CA-LCSA shows a practical approach to model the life cycle impacts of the broad system is to start by modelling the technological system at the micro level and then scale it up with the realistic scenario settings that are generated with the knowledge gained from the MFA studies at the meso-level and from the policy/economic studies at the macro level. The combined application of LCA, LCC and SLCA at the project level shows not all the cost items and only one social impact indicator can be modelled in the process-based LCA structure. Thus it is important to address the left out information at the interpretation step.
Conclusions Defining sub-questions on three different levels seems most useful to frame an LCSA study at the early stage of goal and scope definition. Although this study provides some useful steps for the operationlisation of the LCSA concept, it is clear that additional case studies are needed to move LCSA into a practical framework for the analysis of complex sustainability problems.

Keywords Construction and demolition waste · End-of-life concrete recycling · Life cycle sustainability analysis · Life cycle sustainability assessment

Abbreviations

ADR	Advanced dry recovery
CA	Clean aggregate
C&D waste	Construction and demolition waste
EIOA	Environmental input–output analysis
EOL	End-of-life
IOA	Input–output analysis

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LAP2	Dutch second waste management plan
LCA	Life cycle assessment /analysis
LCC	Life cycle costing
LCSA	Life cycle sustainability assessment /analysis
MFA	Material flow account
RBM	Road base material
SLCA	Social life cycle assessment

1 Introduction

1.1 Concept of LCSA

The ever-increasing awareness of the importance of life cycle thinking as a way to face sustainability challenges coined the term *LCSA*, where *LC* means *Life Cycle*, *S* means *Sustainability* and *A* represents either *Assessment* or *Analysis*.

LCS Assessment was proposed to support the product-related decision-making based on a life cycle perspective and the consideration of the three sustainability dimensions (environmental, economic and social). Klöpffer (2008) suggested the formula LCSA=LCA+LCC+SLCA as a way to cover the three dimensions of sustainability in the LCS Assessment for products. To give a guide on how to carry out a LCS Assessment through the combined application of the existing environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA), the UNEP/SETAC Life Cycle Initiative published a LCS Assessment framework (Valdivia et al. 2011). This framework builds upon the ISO 14040 life cycle assessment framework for environmental LCA, comprising four phases: phase 1 LCSA goal and scope, phase 2 LCSA inventory, phase 3 impact assessment and phase 4 LCSA interpretation. Two case studies: Traverso and Finkbeiner (2009) on marble slabs and Lu (2009) on e-waste management were given to illustrate the practical steps of LCS Assessment.

LCS Analysis broadens the scope of LCS Assessment from predominantly product-related questions to questions related to sector or even economy-wide levels. Within the EU project CALCAS,[1] a scientific framework for LCS Analysis was suggested (Heijungs et al. 2010). This framework was further elaborated in Guinée et al. (2011) and is represented in Fig. 1a. It comprises three phases: goal and scope definition, modelling and interpretation. The inventory and impact assessment phases in LCA are merged into one modelling phase. Various life cycle and disciplinary models are involved in the modelling phase to allow the analysis cover different sustainability aspects (environmental, economic and social) at different "objects of analysis" levels (product, meso, or economy). To make the framework operational, a road map and a preliminary number of steps, including "Framing the question for sustainability decision support", "System boundaries", "Interlinking models, variables or results", etc. were proposed in CALCAS. Furthermore, three example applications (Zamagni et al. 2009) were given to illustrate the phase of goal and scope definition (G&SD). The examples show that a comprehensive LCS analysis can be too complex to carry out. As Guinée et al. (2011) stated "for making the LCS Analysis framework operational, substantial research is needed" and "the general scientific challenge is to derive consistent criteria for implementing methods in relation to specific life-cycle based questions". Case studies are encouraged to gain the experience of putting the LCS analysis in practice.

[1] CALCAS (http://www.calcasproject.net/).

1.2 The case of concrete recycling

This paper presents an on-going LCSA study for the case of concrete recycling.

Construction and Demolition (C&D) waste is one of the largest solid waste streams. The main fraction of it is the end-of-life (EOL) concrete generated from demolition. Recycling the EOL concrete into useful materials is an important solution for minimizing the volume of C&D waste. Technology innovations of concrete recycling are strived to improve the product quality and reduce the processing cost at the same time. To achieve this goal, the recent EU-FP7 project—C2CA[2] proposes a system solution. It relies on: (1) improving the dismantling and demolishing of EOL buildings to generate cleaner EOL concrete for recycling; (2) advancing the state-of-the-art recycling technology—ADR (advanced dry recovery) to liberate the EOL concrete into clean aggregates (CA) for concrete mix and calcium-rich fines that can substitute limestone for clinker production in cement kilns; and (3) developing on-line sensors to guarantee the quality of the recycled products. To ensure the proposed solution will lead to a more sustainable C&D waste management, considering the direct and indirect impacts, within the scope of C2CA project, the life cycle environmental, economic and social analyses are planned. The results of the analyses will be used to support eco-design recommendations and policy recommendations at European, national and local levels.

Following the CALCAS framework, we propose five operational steps to implement the C2CA-LCSA (see Fig. 1b, namely: 1. Broad system definition, 2. Making scenarios, 3. Defining sub-questions for individual tools, 4.

[2] C2CA is funded by European Commission within the 7th framework programme under the theme of "Innovative technologies and eco-design recommendations for reuse and recycling of Construction and Demolition (C&D) waste, with a special focus on technologies for onsite solutions" (grant agreement no: 265189). The project spans 4 years, from January 2011 to December 2014.

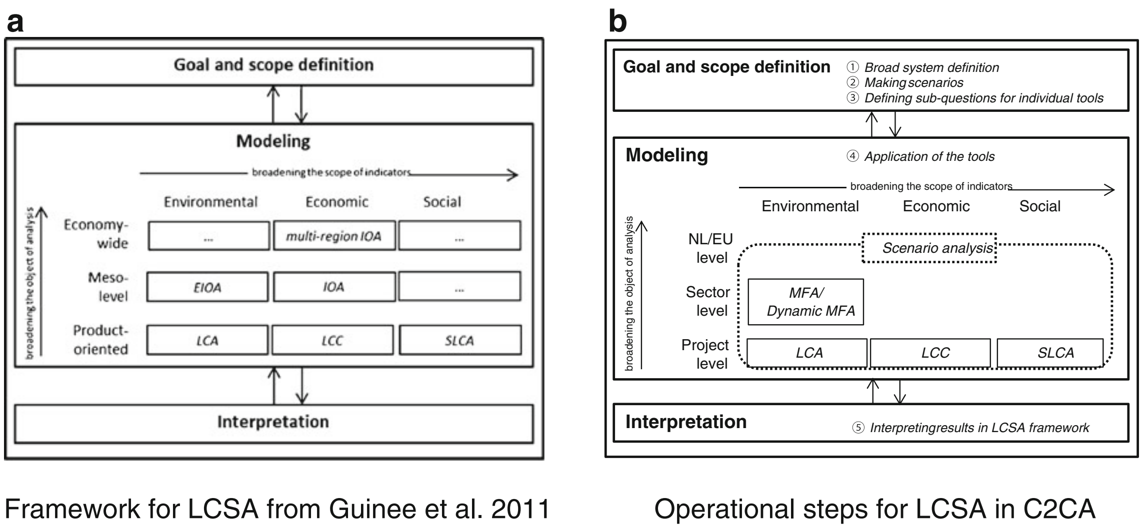

Fig. 1 Framework, methods and steps of life cycle sustainability analysis for C2CA

Application of the tools and 5. Interpreting the results in an LCSA framework). The remaining part of the paper gives a step-by-step explanation on how the procedural steps are implemented in the on-going C2CA-LCSA case study. Focus has been put on the G&SD phase (Step 1–3) to illustrate how to define a doable and meaningful LCSA. Step 4–5 are not complete in the case study and are elaborated theoretically in this paper.

2 Operational steps of LCSA

2.1 Broad system definition

This step is to describe the system under study in an as-broad-as-possible way, in order to identify the problem and decisions at stake, the main interrelations (synergies, conflicts, trade-offs, etc.) between the objects, processes, stakeholders and between the environmental, economic, social domains. Corresponding to the *Product-oriented*, *meso* and *Economy-wide* levels in CALCAS framework, the broad system analysis of C2CA-LCSA is carried out at *Project level*, *Sector level* and *NL/EU level* (see Fig. 1).

2.1.1 NL/EU level

The *NL/EU level* is considered because the C2CA project is initiated to tackle the C&D waste management problem in the Netherlands and Europe. An important goal of the life-cycle sustainability analysis is to formulate policy recommendations, therefore the emphasis of the C2CA-LCSA study at this level is on its policy implications (outer ring in Fig. 2).

In Europe C&D waste is one of the largest solid waste streams. On a medium-term basis, an increase of this stream is anticipated.[3] The common European strategy towards this stream is recycling. The Waste Framework Directive has set the recycling target for the non-hazardous C&D waste to be 70 % by 2020 (2008/98/EC).

In the Netherlands The recycling rate for C&D waste has reached 95 % since 2001, due to the landfill ban which came into force in 1997. EOL concrete represents 40 % of C&D waste. This stream is 100 % recycled with more than 97 % of it used in road construction as road base material (RBM). However, the generation of EOL concrete is expected to increase from 10.5 million ton (Mt) in 2003 to 22 Mt in 2025 (VROM 2008), while road construction will be stable. Consequently, a solution will need to be found for over 10 million ton/a of EOL concrete that cannot be absorbed in roads. A potential outlet for this surplus stream is to process it into CA and use it for new concrete production. But the current method (wet process) to produce CA is costly. Currently, less than 3 % of EOL concrete is processed into CA.

The Dutch government used to encourage the application of recycled C&D waste as aggregates in new concrete. A programme launched in the early 2000s targeted a 25 % replacement of primary aggregates in structural concrete (Institution of Civil Engineers 2003, pp. 2–19). However, due to the lack of evidence that the switch from down-cycling C&D debris in roads to recycling can reduce the

[3] In Europe, an increase of the demolition waste is expected because most European land is already a densely populated area. The limited supply of the development land results in more and more demolition of buildings. For instance, in Germany, new buildings are established on two thirds of all demolished real estate (Tränkler 1994).

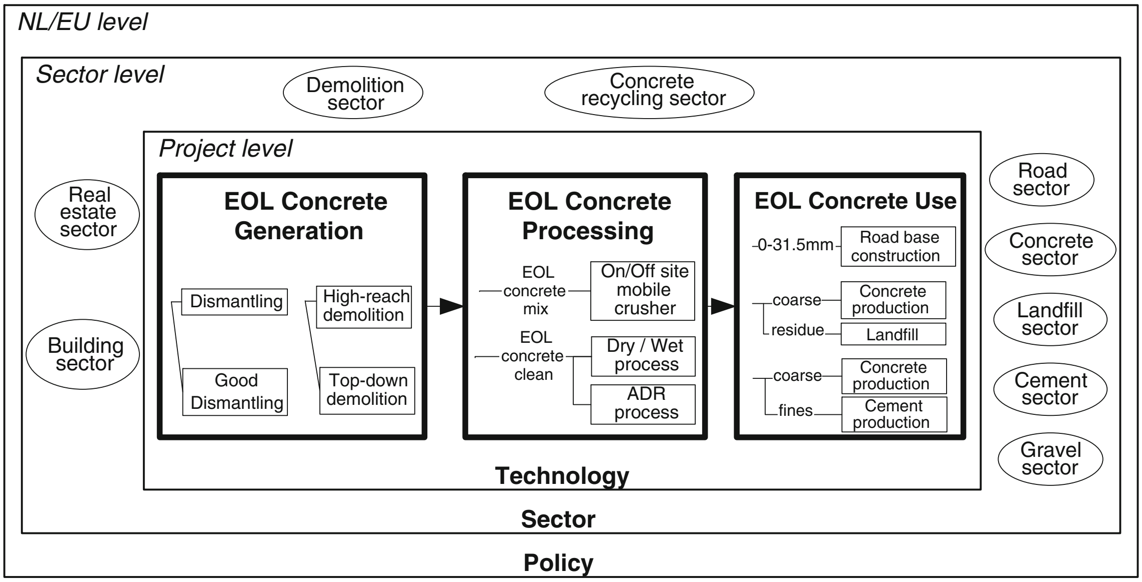

Fig. 2 The broad system of life cycle sustainability analysis for C2CA

life cycle environmental impact, there were no mandatory requirements placed on industry. As a result, with limited interest in the programme the government has dropped the scheme. The recent letter "More value from waste" from the Ministry of Infrastructure and Environment (Atsma 2011) shows such mandatory requirements for concrete recycling that are unlikely to be launched in the near future. The Dutch Second Waste Management Plan (LAP2) for the period 2009–2021 sets the target for the stream of C&D waste as: keeping the current recycling rate[4] of C&D waste and reducing the environmental impact within the life cycle of C&D waste management. Under the new chain approach in LAP2, the C&D waste is selected as one of the seven priority flows, the environmental impact of which needs to be reduced by 20 % by 2015.

2.1.2 Project level

The *Project level* is considered because C2CA is a technology innovation project; the project's scientific/technological achievement is the basis for all the sustainability analysis. The core of C2CA is to advance concrete recycling technology. Since the lifecycle sustainability analysis is also used to support eco-design recommendations, the emphasis of C2CA-LCSA at this level is to identify the hot-spots in the technology system to improve its sustainability. Conceptually, the technology system for concrete recycling is made up of three components: EOL concrete generation, EOL concrete processing and EOL concrete use (central box in Fig. 2). The current and C2CA proposed routes for concrete recycling are:

Current technology to produce road base material EOL concrete is generated from demolition sites. In the Netherlands, to demolish a high-rise building, the normal procedure is first dismantling then demolishing with high-reach method. After that the EOL concrete is generated. The EOL concrete is sent to on-site or off-site crushers to produce RBM. The recycled RBM is used in road base construction. For this application, mixture (up to 50 % by weight) with bricks and other stony materials in the EOL concrete is allowed.

Current technology to produce clean aggregate To generate clean EOL concrete for the production of CA, more careful dismantling and demolishing is needed to keep the concrete stream away from other materials such as bricks. Then the broken concrete is sent to the wet recycling process. In the process the coarse fraction of the broken concrete is washed to produce CA. The recycled CA is used for new concrete production and the residue generated from the washing process is sent to landfill in the form of sludge.

C2CA technology the C2CA project proposes to use smart dismantling and top-down demolition method to generate clean EOL concrete. The broken EOL concrete is then sent to Advanced Dry Recovery (ADR) process to produce CA and the calcium-rich fines. The recycled CA is used for new concrete production and the recycled fines are used for cement production. On-line sensors are used to guarantee the product quality. Recently, a mobile version of the ADR has been

[4] It refers to the recycling rate of C&D waste in the Netherland at 2006, 95 %.

developed, it allows the local reuse of the EOL concrete and therefore a significant reduction in road transport and related impacts.

2.1.3 Sector level

In between the *NL/EU level* and the *project level*, the *sector level* is considered. This is because the interrelations of sectors may constrain the implementation of the innovative technology. For C2CA, the concrete recycling sector is the user of the innovative EOL concrete processing technology. It receives EOL concrete from the demolition sector; it supplies RBM to road construction sector, CA to concrete sector and in future the calcium-rich fines to cement sector; it disposes residuals to the landfill sector. The concrete recycling sector needs to compete with the road construction sector to receive EOL concrete from the demolition sector and need compete with the gravel sector to sell recycled CA to the concrete sector. The C2CA-LCSA at this level focuses on the interrelations between the sectors and the implications of those interrelations for technology development and policy making (middle ring in Fig. 2). Based on the interviews with the experts from the construction, demolition and concrete recycling companies, the most important interrelations that have been identified are:

> *Concrete recycling sector and concrete sector*: Currently, the amount of gravel in concrete that can be replaced by the recycled aggregates is far higher than the amount of the CA that can be produced from the EOL concrete.
>
> *Concrete recycling sector, gravel sector and concrete sector*: The next couple of years, an ample supply of natural gravel and sand will be generated by the deepening of rivers in the South of the Netherlands. A significant increase of the use of recycled aggregates as a replacement for natural gravel in the concrete sector is therefore not expected in the near future.
>
> *Concrete recycling sector, road sector, demolition sector and Landfill sector*: Until now the road construction sector pays a good price for the RBM generated from the demolition sector. The method that the concrete recycling sector currently uses to produce CA from EOL concrete is very costly. Only 2 % EOL concrete is recycled as CA in the Netherlands. However, a decade from now, due to the ageing of the Dutch building stock, a steep increase of demolition waste and especially EOL concrete is expected. But the road construction in the Netherlands will remain stable. Without technological innovation in the concrete recycling sector, demolition companies will bear a high disposal cost for the EOL concrete. When recycling turns to be too expensive, some EOL concrete might be mixed with other demolition waste and end up in landfills, though by law recyclable C&D waste is not allowed to be landfilled in the Netherlands.
>
> *Concrete recycling sector, cement sector, demolition sector and road sector*: In the C2CA project, a concrete recycling technology is developed which allows the production of calcium-rich fines from EOL concrete. If the quality of the fines is good enough, considering the huge cement production capacity, all the recycled fines can be absorbed in the cement sector. Since the recycled fines can substitute limestone for clinker production, the CO_2 emission from the cement kilns will be reduced. Therefore, the cement sector might pay concrete recyclers for the fines from EOL concrete. In that case, the gate fee that is charged to the demolition companies who need dispose the EOL concrete can be lower. When the market price for CO_2 credits increases, higher price for recycled fines from EOL concrete might be expected and the concrete recyclers might pay a good price to buy the clean EOL concrete from the demolition companies. Ultimately, this could lead to supply problems for RBM for the road construction sector.

To this end, the mechanisms[5] that can be considered in the C2CA-LCSA are listed in Table 1.

As the target audience of the study—policy makers have the most comprehensive perspective, considering not only a local improvement but also the avoidance of problem shifting to the meso- and macro level, based on the analysis above, the broad system for C2CA-LCSA study is defined as a nested system shown in Fig. 2. The core is the *project level*, focusing on technology. Surrounding it is the *sector level*, setting physical constraints. Embracing them is the *NL/EU level*, giving policy conditions. This nested view is used as a frame to integrate the studies at different levels into one piece of LCSA work.

2.2 Making scenarios

Making scenarios is the second step in goal and scope definition. It forms the basis for the modelling in the sustainability assessment.

As described in the broad system analysis, the problem of the EOL concrete management in the Netherlands is: *In the coming years, a significant amount of surplus EOL concrete that cannot be absorbed in road construction is expected. The current option for this flow is to produce CA for new concrete production, but the process is costly.* The C2CA project proposes an innovative route to process the surplus EOL concrete

[5] Within the context of LCA, a mechanism is in the first place a causal relationship that connects the level of two activities (Heijungs et al. 2009).

Table 1 Mechanisms identified for life cycle sustainability analysis in C2CA

Type	Mechanisms	Level
Technological	Increase of building demolition leads to increase of EOL concrete generation	Project
	Road construction cannot absorb increased EOL concrete which leads to an increase in processing of EOL concrete into CA	
	Using recycled CA in concrete production leads to using less natural gravel	
	Processing EOL concrete by the wet recycling process induces sludge landfill	
	Processing EOL concrete by the ADR process generates calcium-rich fines that can be used in cement production	
	Using calcium-rich ADR fines to replace limestone in cement production induces CO_2 emission reduction	
Economic	Increase of EOL concrete generation implies a decrease of the price the road construction sector will pay for EOL concrete	Sector
	Increase of EOL concrete that cannot be absorbed by road construction implies an increase of the gate fee that recycling plants will charge for EOL concrete	
	When recycling turns to be too expensive, some EOL concrete might be mixed with other demolition waste and end up in landfills	
	CO_2 emission decrease in cement production implies saving of CO2 credits	
Legislative	Landfilling EOL concrete is not allowed in the Netherlands	NL/EU
	In NL, the environmental impact of C&D waste needs to be reduced by 20 % by 2015	
	In the EU, 70 % of non-hazardous C&D waste should be recycled by 2020	

into CA and calcium-rich fines for new concrete and cement production. As illustrated in Fig. 3, if the generation of EOL concrete increases steadily from 2003 to 2025 but the demand for EOL concrete from road construction will reach the maximum and become stable from 2015 onwards, the decision at hand is whether to develop C2CA technology to treat the surplus EOL concrete expected in the coming decade.

At the project level, there are two extreme scenarios for the technology: the *BAU* (*business-as-usual*) *scenario* and the *C2CA scenario*. The *BAU scenario* represents the situation without technological innovation. According to the Dutch landfill ban, dumping recyclable materials such as EOL concrete is not allowed. The only alternative is to recycle a large amount of EOL concrete through the wet recycling process to produce CA. Under the BAU scenario,

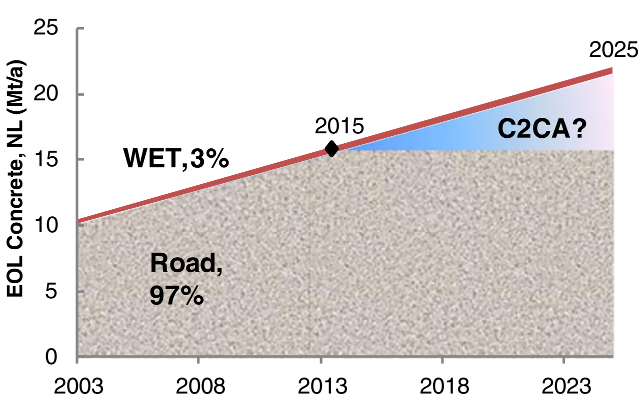

Fig. 3 EOL concrete generation and recycling options in the Netherlands

the technology system to recycle the concrete from the EOL building to be demolished in the C2CA project is illustrated in Fig. 4a. The building is demolished with common Dutch dismantling and demolition method to generate EOL concrete. Part of the EOL concrete is mixed with bricks and sent to a breaker to make RBM. The remaining clean EOL concrete is sent to a stationary wet treatment plant. After crushing and washing, the coarse product CA is sold to concrete manufacturers, the fine product (sieving sand) is used as filling material in road base, and the residue (sludge) is landfilled.

The *C2CA scenario* represents the situation that the technological innovations proposed by the C2CA project are fully implemented. Under C2CA scenario, the technology system to recycle the concrete from the EOL building to be demolished within the C2CA project is illustrated in Fig. 4b. The building is broken down with smart dismantling and demolition method to produce cleaner EOL concrete. A mobile ADR processing system is installed at the demolition site to process the EOL concrete into CA and calcium-rich fines. On-line sensor technology is used to guarantee the quality of the products. The high quality CA is used as substitute of virgin gravel in concrete production and the calcium-rich fines are sent to cement producer and used as substitute of limestone in clinker production.

The technological systems presented in Fig. 4 are multifunctional and not directly comparable in classical LCA. Although the main function of both systems is the same "providing a waste management service for the EOL

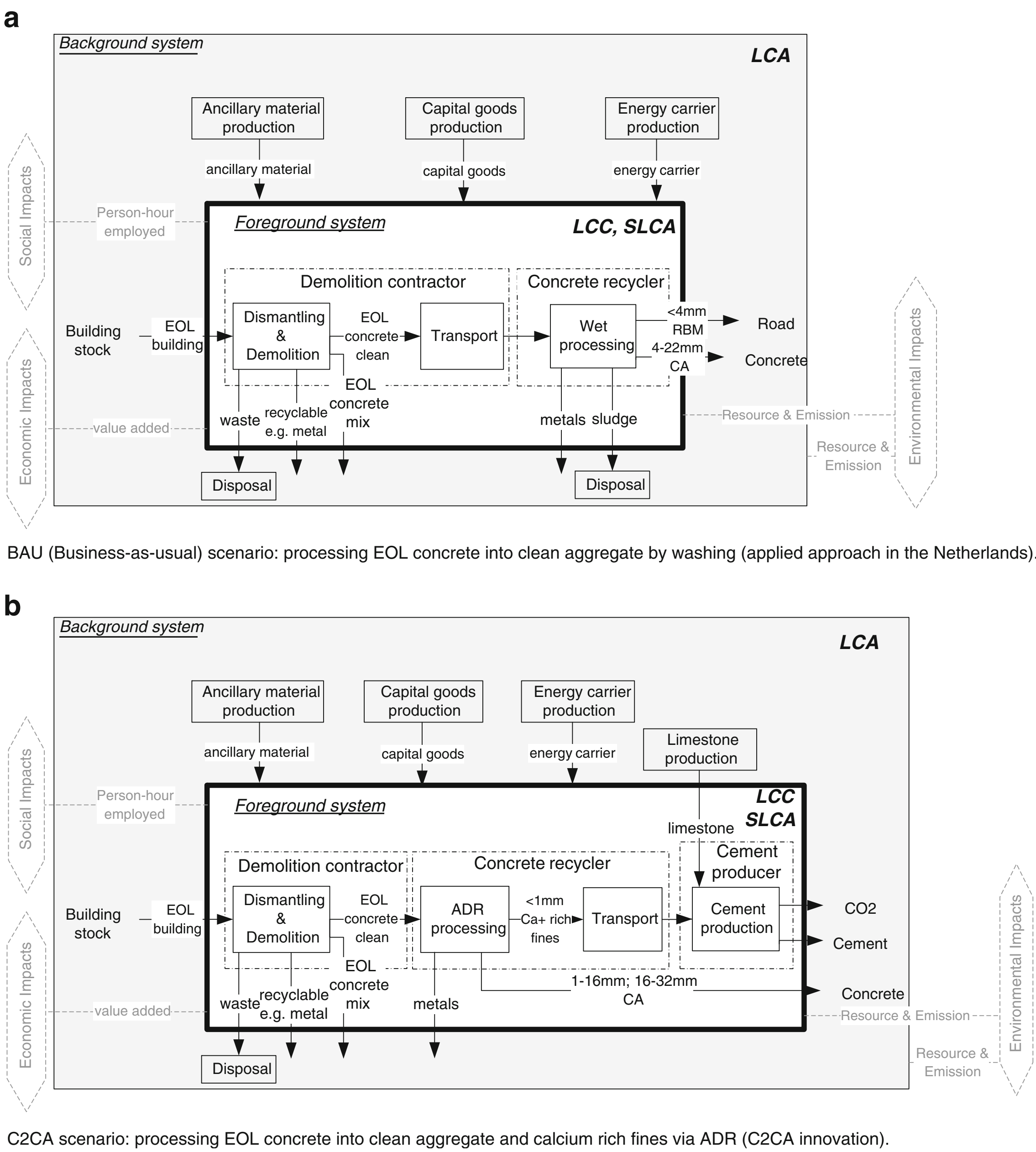

Fig. 4 Technology systems for EOL concrete recycling scenarios

building”. The BAU system also produces CA, RBM and other recyclables, while C2CA system also produces CA, calcium-rich fines and other recyclables. As the product type and quantity of the two systems are different, the two scenarios are not directly comparable. In this study, economic allocation Guinée et al. (2004) is used to transform both systems into mono-functional ones which provide only waste management service. The environmental performance of the system is determined by allocating parts of the impacts to the useful (positive monetary value) materials produced by the system.

As in this case study, the main goal of the LCSA is to generate policy recommendations, comparing the sustainability of the technological systems for one building’s concrete recycling at the project level is not sufficient. The perspective of a nested broad system (see Fig. 2) has to be adopted to investigate the potential of the C2CA innovation to resolve the EOL concrete management problem and to suggest the points where policy regulating is needed to ensure the realization of the potential. Scenario analysis at the sector and NL/EU levels is of utmost important to link the sector knowledge (e.g. business models of the industrial players in the scene of concrete recycling) and policy conditions (e.g. carbon pricing, required recycling rate, minimum percentage of recycled material use, etc.) with the technological system.

At the start of the C2CA project, two scenarios have been constructed for the technological systems at the project level in today's world. In a second stage, the scenarios about the future economics (e.g. change of scrap prices), policy conditions and sector interrelations (e.g. stock dynamics of buildings and roads) will be constructed based on the policy review, interviews, brain storming within the project workshops and static/dynamic material flow analysis for the relevant sectors. In addition, the paths about how the system will evolve from the current state to the probable future states will be included in the assumptions used to define the scenarios. Frameworks for scenario development proposed in Pesonen et al. (2000), Fukushima and Hirao (2002) and Börjeson et al. (2006) are used as a methodological guide for the scenario construction procedure.

2.3 Defining sub-questions for individual tools

Linking sustainability questions with suitable models and methods is the main challenge in putting LCSA in practice. The CALCAS examples Zamagni et al. (2009) suggest five steps to realize this: "Question framing", "Objects of the study", "Sustainability aspects", "Mechanisms" and "Methods and models". In our approach "Question framing" and "Methods and models" are merged into "Defining sub-questions for individual tools" as the third step for goal and scope definition. In this step sub-questions that can be answered by individual (existing) analytical tools are formulated.

As C2CA is a technology innovation project, the main question for C2CA-LCSA is "*Can the technological innovation* (*smart dismantling and demolition+ADR+quality control sensor*) *proposed by the C2CA project improve the sustainability of EOL concrete management from a life cycle perspective*?" As illustrated in the Fig. 1b, the analytical tools LCA, LCC and SLCA are used to investigate the question by modelling the technology systems constructed at the project level. The indicators considered for the life cycle analysis tools and the procedure to select the indicators are presented in the following section. At sector level, the main question is "*To what level can the C2CA innovation be scaled up*?" To answer the question, the analytical tools static MFA and dynamic MFA are needed in this case study. The former is useful to investigate the constraints for C2CA application due to the material linkages, and the latter is useful to estimate the trends of future demand for the C2CA innovation. At the economy-wide level, input–output analysis (IOA) could be used as a tool for the analysis. However, the current resolution of the input output tables is not sufficient to answer a question like "*How will the economy be affected if 5% of limestone in clinker production can be substituted by calcium-rich fines recycled from EOL concrete*". We decided not to use this IOA, but to use the more soft approaches such as interviews and brainstorming to catch the economic and policy relevant issues at the NL/EU levels. Finally, to integrate the knowledge of all the levels, scenario analysis is used to introduce the sector dynamics and the NL/EU economic/policy conditions into the life cycle modelling of the technology systems.

Table 2 presents the sub-questions formulated for the individual tools at each of the three "objects of analysis" levels (project, sector and NL/EU levels).

2.4 Application of the tools

In this step, modelling tools are used to produce results as a base for the answering of the sub-questions. Sub-questions defined in the previous step are analysed through the use of individual analytical tools.

The tools used to calculate the life cycle impacts of the technology system are the SETAC/ISO environmental LCA (ISO 2006a, b), the LCA-type environmental LCC (Swarr et al. 2011), and the UNEP/SETAC SLCA (Benoit and Mazijn 2009). First, the models are built at the project level. Figure 4 represents the physical relations within the *BAU scenario* and the *C2CA scenario*. The figure illustrates the scope of LCSA, which is the broadening of scope from environmental aspects addressed in LCA to the economic aspects addressed in LCC and the social aspects addressed in SLCA. The functional unit for comparison is the disposal of *x* ton of materials from the EOL building.

The LCA is performed as process-based assessment. In the LCA, a set of midpoint and endpoint impact categories that are recommended by the International Reference Life Cycle Data System (ILCD) are used. The midpoint assessment is performed with the methodologies of EDIP and/or CML and for the calculation of end-point results ReCiPe is applied.

The environmental LCC defined by the "code of practice" Swarr et al. (2011) is used to assess the economic dimension of the sustainability. The indicator used in the LCC is the value added of the processes in the foreground system as illustrated in Fig. 4. For each process there are two economic indicators: cost and revenue. The choice to use the value added as the only indicator is to avoid double counting for the technology system made by a chain of processes. Since the revenue of the supply process is the cost of the receiving process, only the net economic effect, that is, the value added of the system is used as the indicator for the economic performance of the system.

The SLCA aims to assess the performance of the companies in the chain under different scenarios on the basis of twelve indicator sub-categories, selected by stakeholders in a bottom-up process. As a starting point for indicator selection, the *Guidelines for Social Life Cycle Assessment of Products* were used. For the purposes of the C2CA SLCA, the indicators were selected for type 1 impact categories,

Table 2 Sub-questions and individual tools for life cycle sustainability analysis in C2CA

Main question: Can the technological innovation (smart dismantling and demolition+ADR+quality control sensor) proposed by the C2CA project improve the sustainability of EOL concrete management from a life cycle perspective?	
Sub-questions	Individual tools
Project level:	
To recycle the concrete from the EOL building that was demolished within the C2CA project, the questions are:	
[environmental]	LCA
• Can the C2CA innovation lead to a reduction of the environmental impact from a life cycle perspective? In which part of the chain can this potential reduction be achieved?	
[economic]	LCC
• Can the C2CA innovation lead to a decrease of the economic cost and/or an increase of the value added in the chain? In which part of the chain can most of this additional value creation be achieved?	
[social]	SLCA
• What is the social performance of within the chain and in what way can the C2CA innovation improve/affect it?	
Sector level:	
To what level can the C2CA innovation be scaled up? Can it be applied on the level needed for the EOL concrete recycling in the Netherlands in the next decade? How the flows of concrete and concrete recycling products between the involved sectors will change over time if the C2CA technology will not be applied?	
• What is the trend in the EOL concrete generation from the obsolete buildings in the Netherlands?	Dynamic MFA
• What is the trend in the EOL concrete use in the road construction in the Netherlands?	Dynamic MFA
• What amount of calcium-rich fine products of ADR can be absorbed in the cement industry? MFA	
• What amount of the gravel and sand is used in concrete manufacturing? What amount of natural gravel and sand can/will be produced in the near future? To what extend can recycled aggregates substitute natural gravel and sand in concrete manufacturing?	MFA
• What is the capacity of the wet processing route in concrete recycling? How much sludge is produced in wet processing? How much sludge can be landfilled?	MFA
NL/EU level:	
• What policies influence concrete recycling?	Policy review
• What are the potential policy strategies and economic instruments for the future EOL concrete management?	Interview, workshop brain storming
Integration of all levels:	
• How will the technological systems for concrete recycling in the Netherlands develop in the next decade, with and without C2CA innovation?	Scenario analysis (using results from MFA, dynamic MFA)
• How can the technological systems be influenced by the potential policy and economic instruments?	Scenario analysis (using knowledge from policy review, interview and workshop brain storming)
• What is the sustainability performance of the future technological systems for concrete recycling in the Netherlands, with and without C2CA innovation?	LCA+LCC+SLCA (at large scale, based on project level models, using results from scenario analysis)

following a three-step procedure: (1) sub-category screening; (2) sub-category selection; (3) selection of indicators for each selected sub-category. At the third stage, indicators for each sub-category were selected from the suggested indicators in the guidelines, as each indicator sub-category is further defined by at least two indicators. The indicators for the type 1 impact categories are based on corporate social responsibility and global reporting initiative, which

assess company performance towards social issues of concern. Therefore, they can be viewed as indicators reflecting the performance of the chain of companies involved in building demolition, EOL concrete recycling, cement and concrete production. In addition to the foreground system illustrated in Fig. 4, the background system will be assessed on the basis of generic data. However, as shown in Fig. 4, in the C2CA-LCSA, only the indicator "number of person hours employed" is used in the modelling because so far it is the only quantitative indicator in our set of selected indicators that can be currently linked with unit processes.

At the moment of compiling of this paper, only the first stage of LCSA at the project level was completed. Later, the tactical scenarios will be constructed to scale up the technology systems to the national level in the Netherlands. The analytical tools MFA and dynamic MFA will be used to generate the information for the scenario construction. However, the life cycle modelling tools will be the same: a combined LCA, LCC and SLCA.

Ideally, the LCA, LCC and SLCA should be seen as three ways of looking at the same system Heijungs et al. (2010). However, the experience at the project level shows that the implementation of LCSA using the modelling structure of a process-based LCA is problematic. Not all the costs (e.g. overhead, profit and loss) can be explicitly linked with the unit process and most of the qualitative SLCA indicators can neither be linked with the unit process nor with the functional unit. The inability to link the SLCA assessment to the functional unit is discussed in the SLCA literature. It is generally accepted that in SLCA it is the performance of the companies, implementing the processes of LCA, which is accessed, though it cannot be directly calculated for the functional unit of the LCA study. Thus, it is important to address the information that is left out from the modelling in a broad system perspective in the next step of LCSA: interpretation.

2.5 Interpreting the results in an LCSA framework

Based on the data collected within the case study, the question whether the C2CA innovation can lead to a reduction of the environmental impact for the EOL concrete management from a life cycle perspective can be answered by comparing the life cycle environmental impacts of the *C2CA scenario* and the *BAU scenario*. Results at the project level imply that the main environmental impacts in the chain come from the background processes related to energy inputs. The *C2CA scenario* shows better environmental performance mainly because of reduced energy consumption in processing EOL concrete and transportation. Next to that, the avoidance of sludge treatment and the replacement of limestone in cement production produced additional environmental benefits for the C2CA technology.

The question whether the C2CA innovation leads to an increase of the value added in the chain can be answered by the parallel LCC study on the foreground system. Results at the project level show that the value added in the EOL concrete management chain in the *BAU scenario* is negative, due to the expensive sludge disposal and the current low price of natural gravel (a price reference to the recycled CA). Under current market conditions, a mobile ADR plant may achieve a positive value added due to the reduction in transportation and energy consumption. Further value creation in the *C2CA scenario* can be achieved if cement producers are willing to pay for the calcium-rich ADR fines.

The results at project level for the SLCA of the foreground system, calculated on the basis of the indicators for the abovementioned sub-categories, show some differences in both scenarios. The differences come from the individual performance of the companies, implementing the processes in the system and the level of their participation in the product chain under different scenarios.

Results on the project level show that the *C2CA scenario* might deliver some environmental and economic benefits for EOL concrete recycling. However, if the application of C2CA innovation will be scaled up to the national level in the Netherlands, scenario analysis should be performed based on the MFA study for the interrelated sectors and the probable policy and economic situations in the Netherlands and the Europe. A broad system perspective is necessary to integrate the problems at the macro level (NL/EU level), the constraints from the meso-level (sector level) into the life cycle models originally built at the micro (project level). Thus it allows use the LCSA to support both the eco-design recommendations at the project level and the policy recommendations at the NL/EU level.

3 Conclusions and outlook

With an on-going case study on concrete recycling, this article provides a step-by-step description on how a Life Cycle Sustainability Analysis can be implemented in practice. Five optional steps are proposed in the framework of LCSA. Current obtained experience from the case study shows that the distinction of "levels of objects" for analysis is useful to structure the LCSA study at the Goal and Scope definition stage. The C2CA-LCSA shows a practical approach to model the life cycle impacts of the broad system is to start by modelling the technological system at the micro level and then scale it up with the realistic scenario settings that are generated with the knowledge gained from the MFA studies at the meso-level and from the policy/economic studies at the macro level. The combined application of LCA, LCC and SLCA shows not all the cost items (such as overhead, profit and loss) and only one social impact indicator can

be modelled in the process-based LCA structure. Thus it is important to address the left out information at the interpretation step. The C2CA-LCSA provides a useful case study to gain additional experience on using a broad system perspective to facilitate this procedure. The categorizing of sub-questions on three different levels seems useful. Although this study provides some useful steps for the operationlisation of the LCSA concept it is clear that additional cases studies are needed to move LCSA into a practical framework for the analysis of complex sustainability problems.

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References

Atsma J (2011) More value from waste. A letter from Ministry of Infrastructure and Environment. The Hague, August 25, 2011

Benoit C, Mazijn B (2009) (eds) Guidelines for Social Life Cycle Assessment of Products. Paris. 104 pp. http://lcinitiative.unep. Accessed at 6 June 2012Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45:90–96

Börjeson L, Höjer M, Dreborg KH, Ekvall T, Finnveden G (2006) Scenario types and techniques: towards a user’s guide. Futures 38(7):723–739

Fukushima Y, Hirao M (2002) A structured framework and language for scenario-based life cycle assessment. Int J Life Cycle Assess 7(6):317–329

Guinée JB, Heijungs R, Huppes G (2004) Economic Allocation: Examples and Derived Decision Tree. Int J Life Cycle Assess 9(1):23–33

Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buinamici R, Ekvall T, Rydberg T (2011) Life cycle assessment: past, present, and future. Environ Sci Technol 45:90–96

Heijungs R, Huppes G, Guinée JB (2009) A scientific framework for LCA; Deliverable 15 of the CALCAS project. http://www.estis.net/sites/calcas. Accessed 26 January 2012

Heijungs R, Huppes G, Guinée JB (2010) Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. Polym Degrad Stab 95:422–428

Institution of Civil Engineers (2003) A report on the demolition protocol

[ISO] International Standard Organisation (2006a) Environmental management—Life cycle assessment: Principles and framework. ISO14040, Geneva

[ISO] International Standard Organisation (2006b) Environmental management—Life cycle assessment: Requirements and Guidelines. ISO14044, Geneva

Klöpffer W (2008) Life cycle sustainability assessment of products. Int J Life Cycle Assess 13(2):89–95

Lu B (2009) Integrated LCA of Obsolete PC Recycling System, Research Center For Eco-Environmental Sciences, Chinese Academy of Sciences, Proceedings of the 2nd Life Cycle Management China Conference, Beijing

Pesonen HL, Ekvall T, Fleischer G, Huppes G, Jahn C, Klos ZS, Rebitzer G, Wenzel H (2000) Framework for scenario development in LCA. Int J Life Cycle Assess 5(1):21–30

Swarr T, Hunkeler D, Klöpffer W, Pesonen H-L, Ciroth A, Brent A, Pagan B (2011) Environmental Life Cycle Costing: A Code of Practice. SETAC Press, Pensacola

Tränkler JOV, Walker I (1994) Studies in Environmental Science 60: Environmental Aspects of Construction with Waste Materials. In: Goumans JJJM, van der Sloot HA, Aalbers TG (eds) Studies in Environmental Science 60: Environmental Aspects of Construction with Waste Materials. Proceedings of the 2nd WASCON Conference. Elsevier Science, Amsterdam, pp 621–632

Traverso M, Finkbeiner M (2009) Life Cycle Sustainability Dashboard, Proceedings of the 4th International Conference on Life Cycle Management: Cape Town, South Africa, 2009

Valdivia S, Ugaya CML, Sonnemann G, Hildenbrand J (2011) (eds) Towards a Life Cycle Sustainability Assessment. Making informed choices on products. Paris ISBN: 978-92-807-3175-0. http://lcinitiative.unep.fr. Accessed at 6 June 2012

[VROM] Ministry of Housing, Spatial Planning and the Environment (2008) National Waste Management Plan (LAP) 2009 – 2021: Towards a material chain policy. www.vrom.nl. Accessed 26 January 2012

Zamagni A, Buttol P, Buonamici R, Masoni P, Guinée JB, Huppes G, Heijungs R, van der Voet E, Ekvall T, Rydberg T (2009) Blue Paper on Life Cycle Sustainability Analysis; Deliverable 20 of the CALCAS project. http://www.estis.net/sites/calcas. Accessed at 6 June 2012